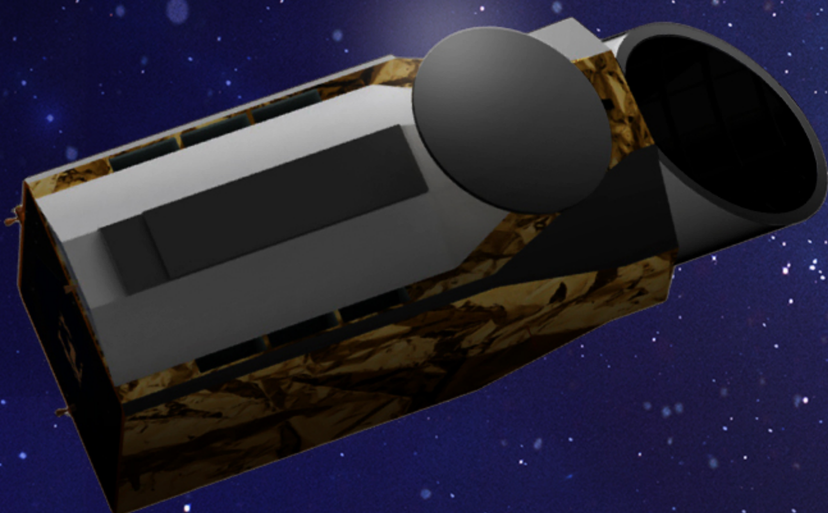
HabEx

Habitable Exoplanet Observatory



Baseline Architecture

Stefan Martin
Jet Propulsion Laboratory,
California Institute of Technology

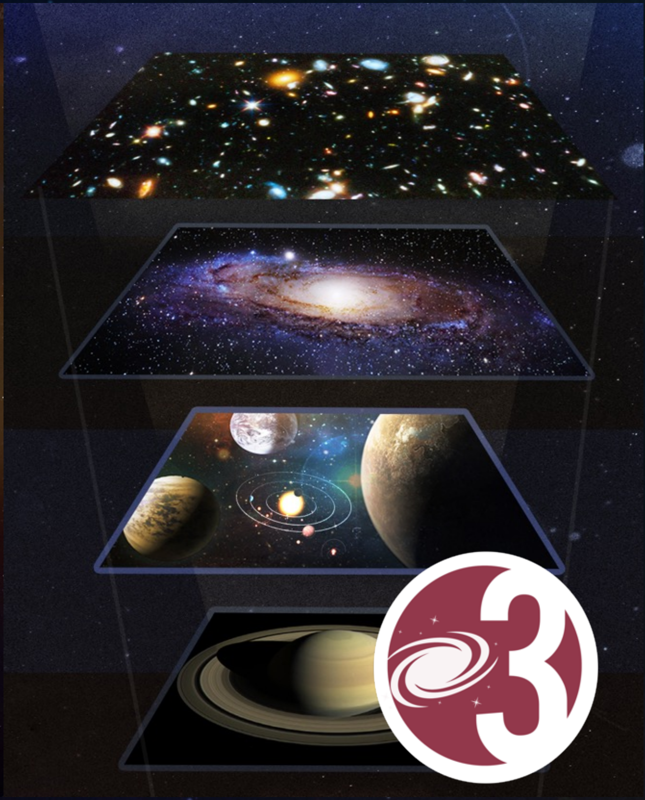
© 2019 California Institute of Technology. Government sponsorship acknowledged.

HabEx

Science Goals

Seek out nearby worlds and explore their habitability

Map out nearby planetary systems and understand their diversity



Enable new explorations of astrophysical systems in the UV to near-IR

HabEx — Preferred Architecture—4H

Telescope:

- 4 m off-axis f/2.5 Al-coated monolith

Instruments:

- Coronagraph Instrument (HCG)
- Starshade Instrument (SSI, used with a 52 m Starshade)
- UV Spectrograph (UVS)
- HabEx Workhorse Camera (HWC)

Launch:

- SLS Block 1B (Telescope)
- Falcon Heavy (Starshade)
- L2 orbit

Timeline:

- Launch: Mid-2030s
- Nominal operation: 5 years, Capability: 10 years

Studied a total of 9 architectures:
4 m/3.2 m/2.4 m × Hybrid/Starshade-Only/Coronagraph-Only

The Next-Generation UVOIR Great Observatory

HabEx

HST

	HabEx	HST
Aperture	4.0 m unobscured	2.4 m obscured
Diffraction Limit	400 nm	500 nm
Slew Rate (180 deg)	20 min (typical), 5 min (max)	~30 min (max)
Pointing Accuracy	0.7 mas	5 mas (typical), 2 mas (best)
Spatial Resolution	25 mas	50 mas
Effective Area* (@200 nm)	10,000 cm^2	700 cm^2
Micro-shutters	Yes	No
Serviceable	Yes/Robotic	Yes/Astronaut

* Effective area is clear aperture multiplied by throughput and quantum efficiency

HabEx Instruments

UV Imager & Spectrograph (UVS)

Imaging Channel	115 - 370 nm
Spectroscopy Channel	• 115 - 320 nm with R=500 to 60,000 • 320 - 370 nm with R=500 or 1,000
Field of View	• 3 x 3 arcmin^2 • Micro-shutter Array for MOS: 2 x 2 array of 171 x 365 apertures
Effective Collecting Area	10x HST/COS

Starshade Instrument (SSI)

UV Channel	200 to 450 nm Imager + Grism at R=7
Visible Channel	450 - 975 nm Imager + IFS with R=140
Near Infrared Channel	975 - 1800 nm Imager + IFS with R=40
High Contrast Region	IWA = 58 mas (from 300 to 1000 nm) OWA = 6” (Imager) / 1” (IFS)
Raw Contrast	10^{-10} at IWA over 107% Bandwidth (nominally 300 to 1000 nm)

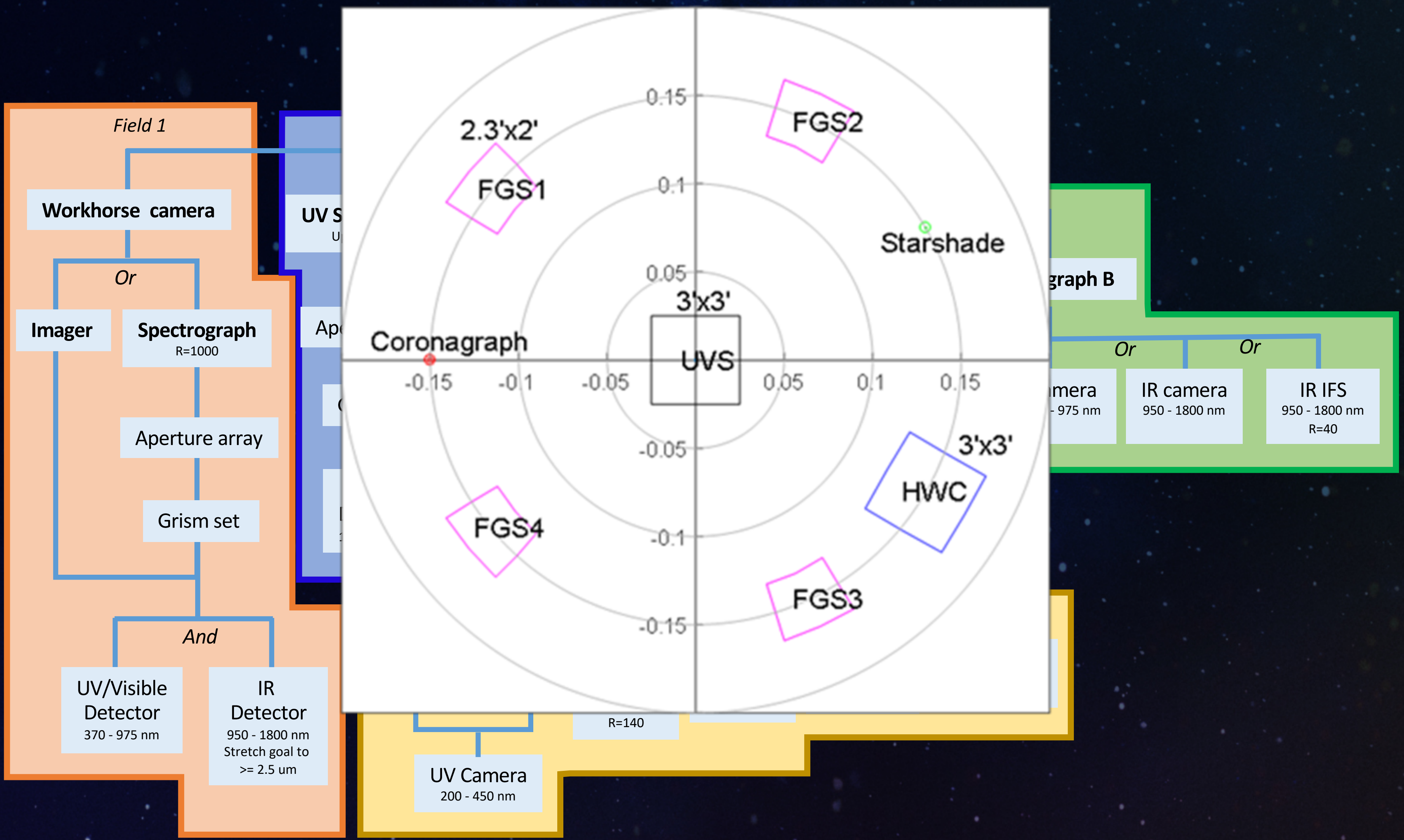
Coronagraph (HCG)

Baseline	Vector Vortex (Charge 6)
Visible Channels (1 per Polarization)	450 - 975 nm Imager + IFS with R=140
Near Infrared Channel	975 - 1800 nm Imager + IFS with R=40
High Contrast Region	IWA = 2.4 l/D (62 mas at 0.5 mm) OWA = 32 l/D (830 mas at 0.5 mm)
Raw Contrast	2.5 x 10^{-10} at IWA over 20% Bandwidth 40x better than WFIRST CGI
Features	Active Low Order Wavefront Sensing & Control with two 64x64 DMs

Workhorse Camera & Spectrograph (HWC)

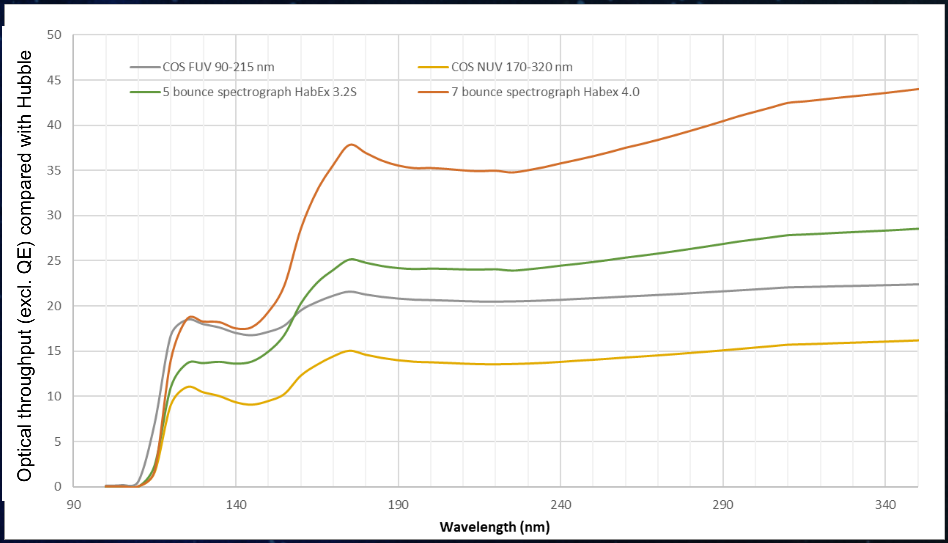
Visible Channel	370 - 975 nm Imager + Grism with R=1000 >2x better resolution than HST < 600 nm
Near Infrared Channel	975 - 1800 nm Imager + Grism with R=1000
Field of View	• 3 x 3 arcmin^2 • Micro-shutter Array for MOS: 2 x 2 array of 171 x 365 apertures

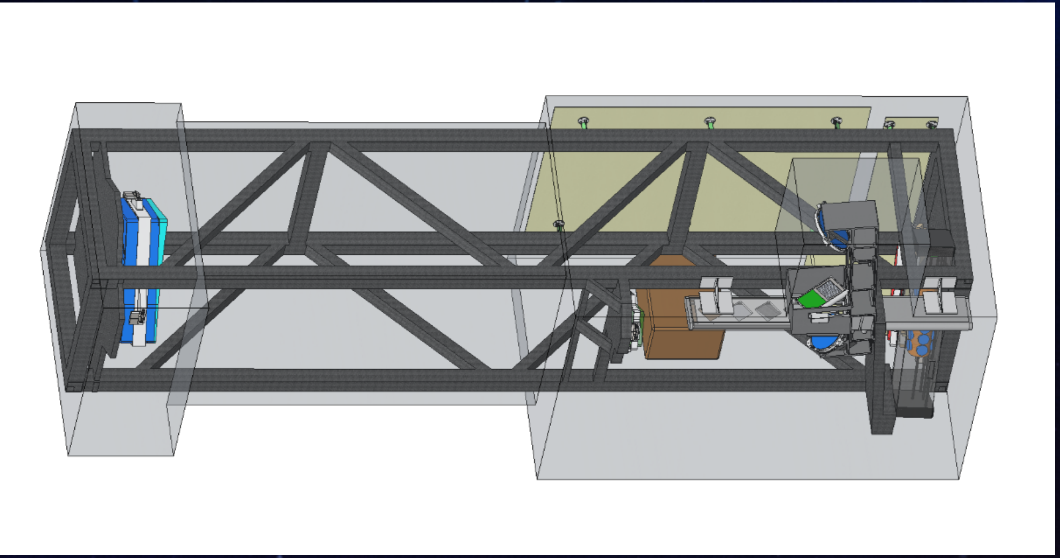
Instrument Complement



Ultraviolet Spectrograph and Camera

- UVS instrument for high-resolution spectroscopy down to 115 nm in the UV.
- Accesses a large number of diagnostic emission and absorption lines available at wavelengths shorter than 0.3 μm.
- Set of 20 diffraction gratings + 1 mirror for imaging, + specialized filters.

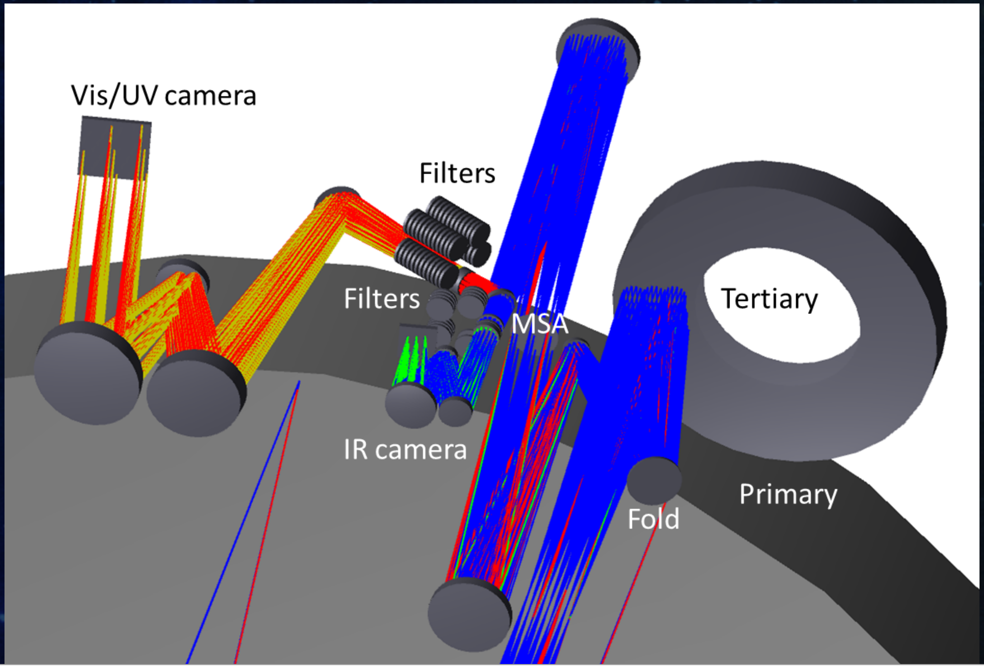


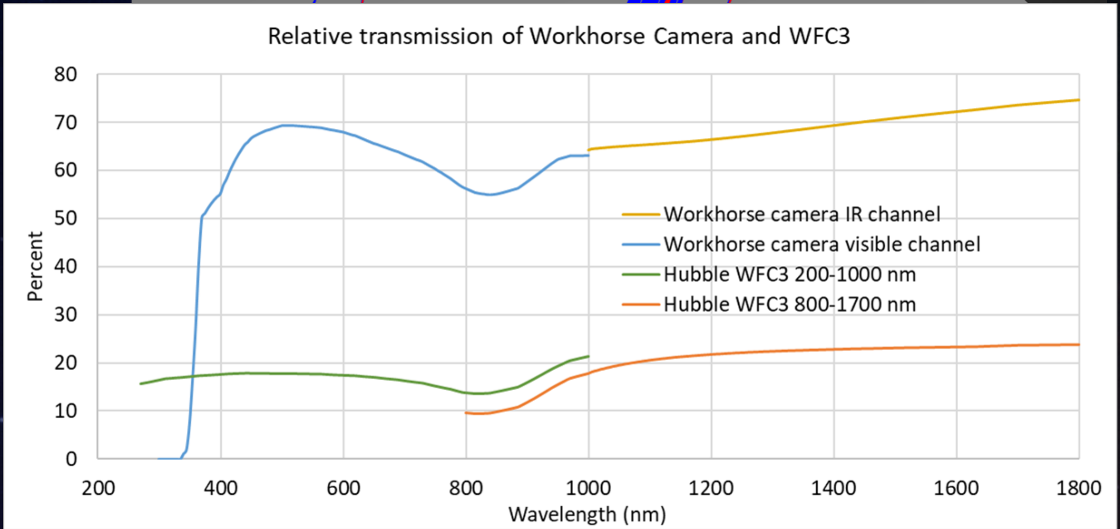


Resolution R	λ min	λ max	Δλ	Resolution R	λ min	λ max	Δλ
λ/Δλ	μm	μm	pm	λ/Δλ	μm	μm	pm
60,000	0.115	0.127	2.01	25,000	0.115	0.146	5.41
60,000	0.127	0.139	2.21	25,000	0.146	0.186	6.88
60,000	0.139	0.153	2.44	25,000	0.186	0.236	8.74
60,000	0.153	0.169	2.68	25,000	0.236	0.300	11.11
60,000	0.169	0.186	2.95	12,000	0.115	0.186	12.29
60,000	0.186	0.204	3.25	12,000	0.186	0.300	19.86
60,000	0.204	0.225	3.58	6,000	0.115	0.300	32.15
60,000	0.225	0.248	3.94	3,000	0.120	0.300	64.29
60,000	0.248	0.273	4.33	1,000	0.120	0.300	185.00
60,000	0.273	0.300	4.77	500	0.120	0.300	185.00

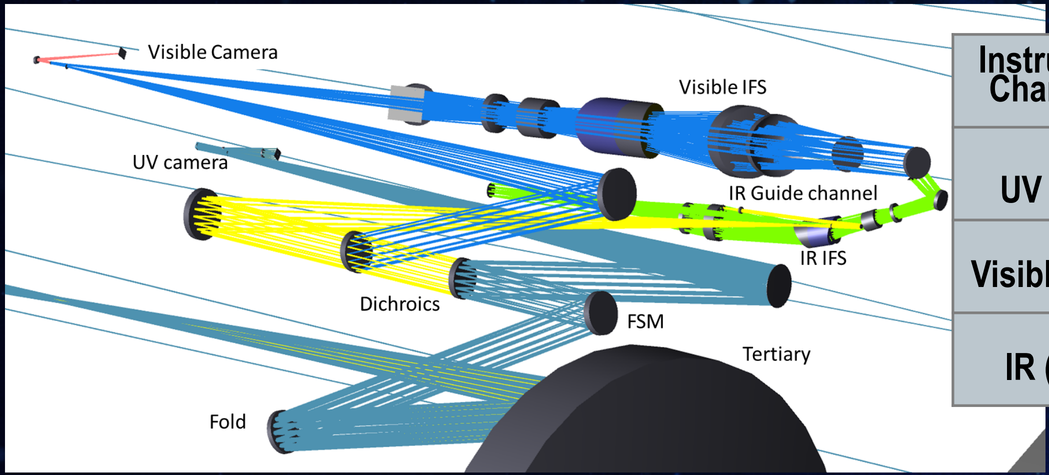
HabEx Workhorse Camera

- Spectral Range (TBR): 150-1800 nm
  - Diffraction limited above 600 nm
  - Visible 370 – 950 nm
  - IR 900 - 1800 nm, stretch 2500 nm
- Spectral Resolution
  - Moderate resolution spectroscopy, R~1000
- Focal planes:
  - e2v CCD203 3x3 12288 total 12 μm pixels
  - Teledyne H4RG10 2x2 8192 total 10 μm pixels
- Aperture Array:
  - GSFC JWST 2x2 180x80 μm * 171x365 apertures
  - Will fold out for camera operation
- Filters/grisms:
  - Up to 48 filters and grisms in the Visible channel.
  - Up to 16 filters/grisms in the IR channel.





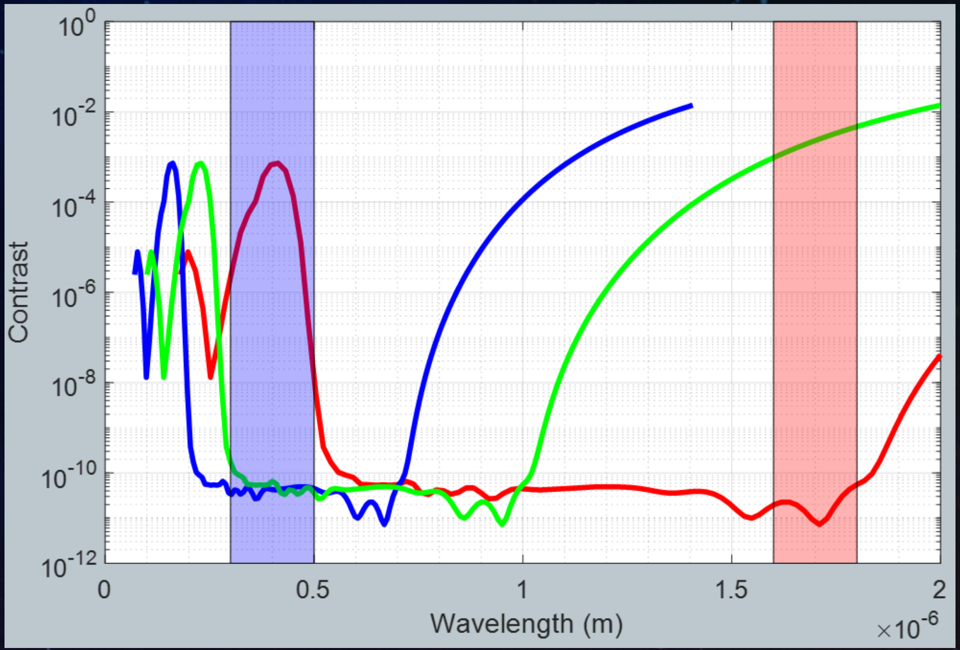
Starshade Instrument



Instrument Channels	UV Science	Visible Science	IR Science
UV (nm)	200–450 (science)	300–450 (science)	300–450 (guide)
Visible (nm)	450–670 (science)	450–1000 (science)	540–1000 (science)
IR (nm)	1600–1800 (guide)	1600–1800 (guide)	975–1800 (science)

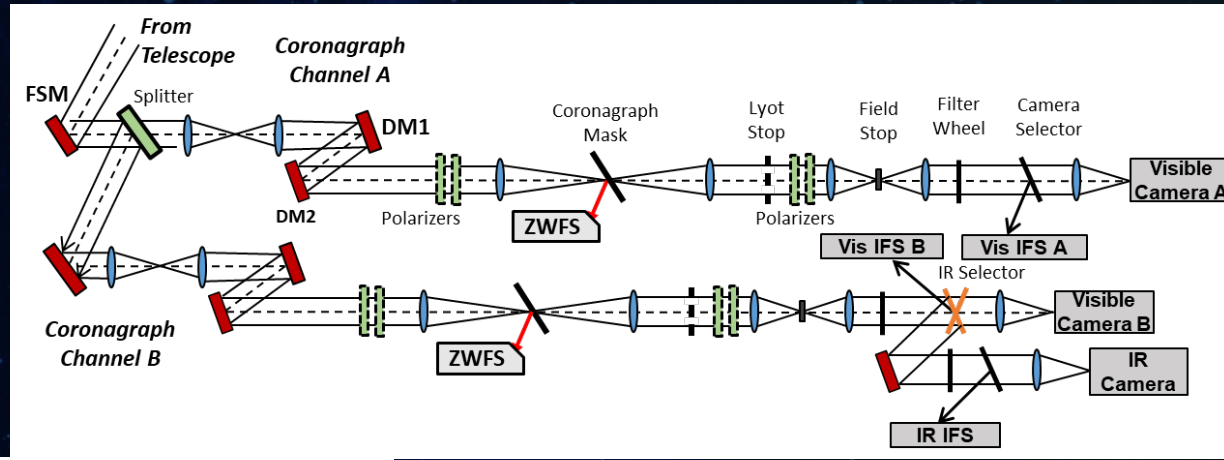
- Starshade diameter: 52 m
- Telescope range: 42,600 km to 114,100 km
- Inner Working Angles: 47, 70, 126 mas

- Formation flying requirement: stay within 1m radius of line of sight to the star
- S5 study (Michael Bottom and Thibault Flinois) has obtained ExEP TAC agreement that Formation Flying is at TRL 5.

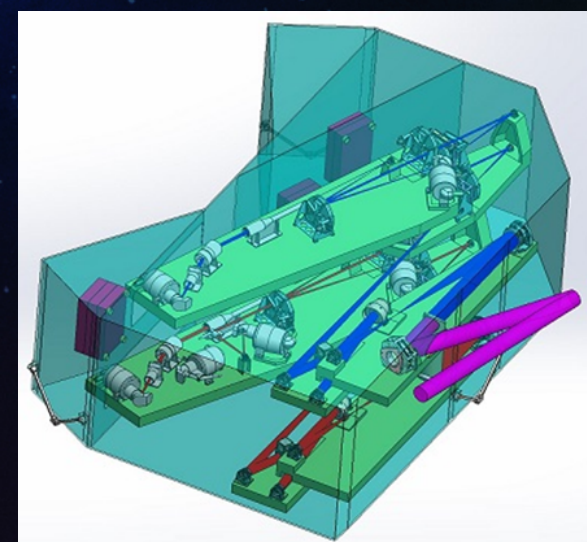


Dual Coronagraphs

Twin coronagraphs observe the same field in orthogonal polarizations.
Within the two channels (A&B) dichroic filters set the optical bandwidth to 20%



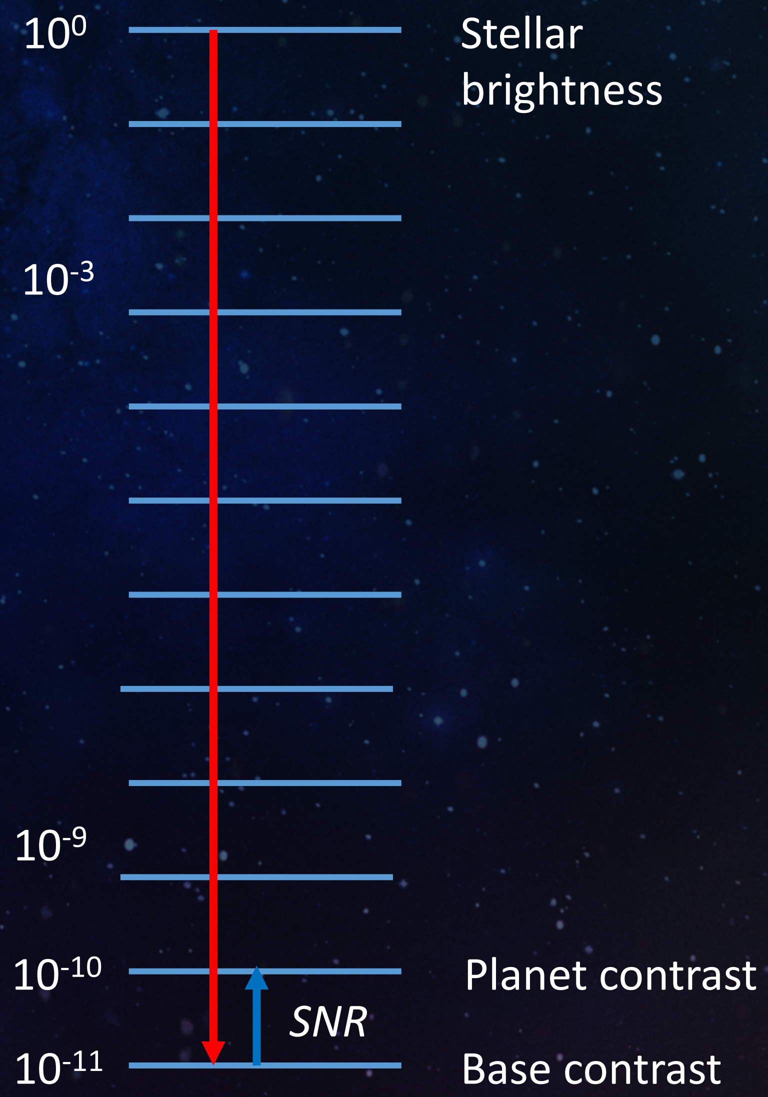
Camera channels		
	Visible Channel (A&B)	IR Channel (B)
FOV	1.5” – 2.7”	3.1”
Wavelength bands	0.45–0.55 μm 0.55–0.67 μm 0.67–0.82 μm 0.82–1.00 μm	0.95–1.8 μm
Pixel resolution	11.6 mas – 17.3 mas	29.9 mas
Telescope resolution	23 mas (at 0.45 μm) 42 mas (at 0.82 μm)	49 mas (at 0.95 μm)
IWA (2.4 λ/D)	56 mas (at 0.45 μm) 102 mas (at 0.82 μm)	118 mas (at 0.95 μm)
OWA (as)	0.74 -1.11	1.57
Detector	1×1 CCD201	1×1 LMAPD
Array width	1024	256×320
Spectrograph channels		
	Visible Channel (A&B)	IR Channel (B)
FOV	1.5” – 2.7”	3.1”
Spectrometer resolution	140	40
Spectrometer type	IFS	IFS
Detector	1/4 CCD282 (EMCCD)	2×2 LMAPD*
Array width (pixels)	2048	2048
Other		
Deformable mirror	2 mirrors 64×64 elements 0.4 mm pitch	
Polarization	Vertical (A channel) Horizontal (B channel)	Horizontal (primarily) Vertical (possible)



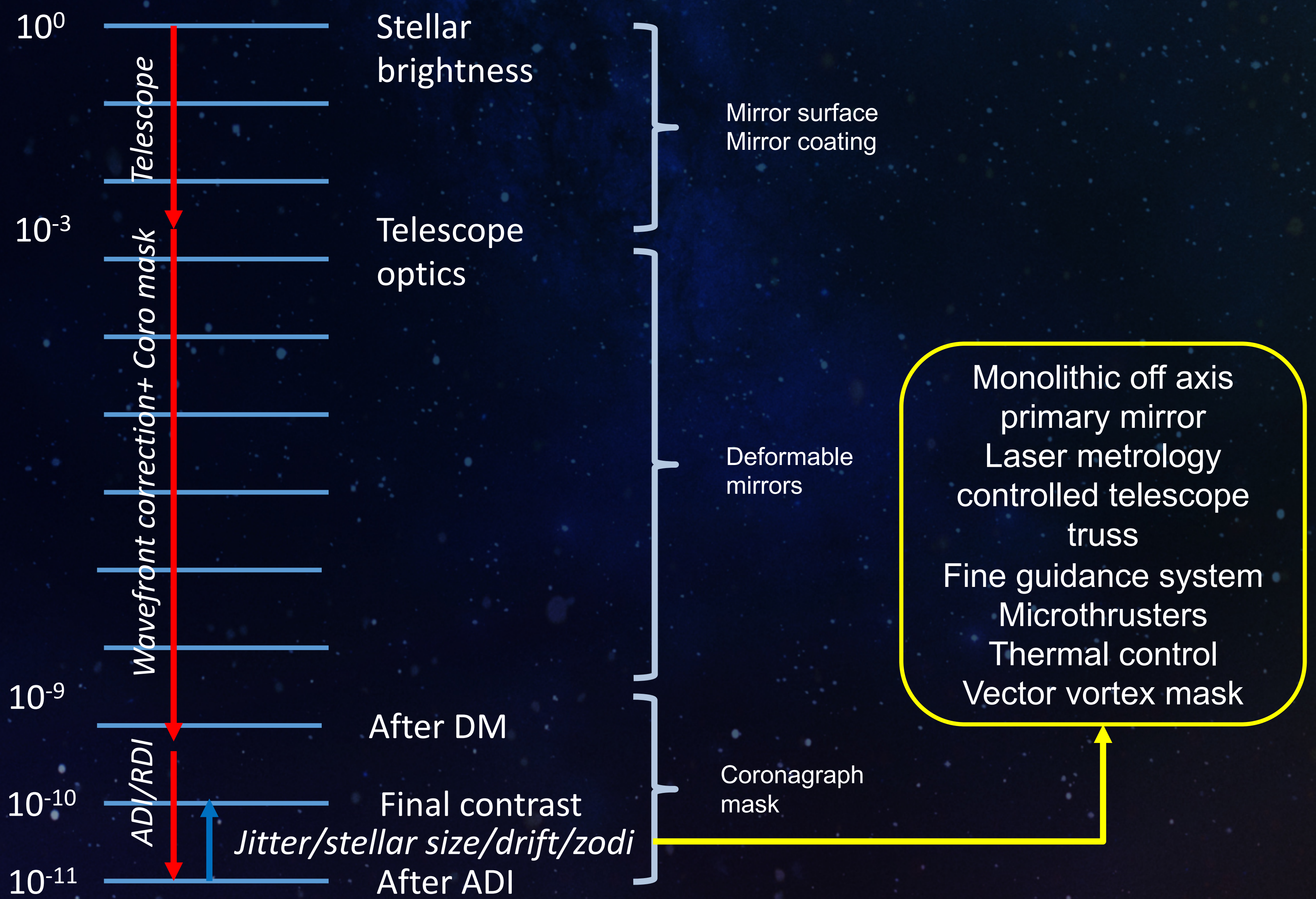
Science Goal #1

What does this involve?

Seek out nearby worlds and explore their habitability



Starlight Suppression using a Coronagraph



Starlight Suppression using a Coronagraph

- Monolithic, off axis, massive primary mirror
- Laser metrology controlled telescope truss
- Fine guidance system
- Microthrusters
- Thermal control
- Vector vortex mask

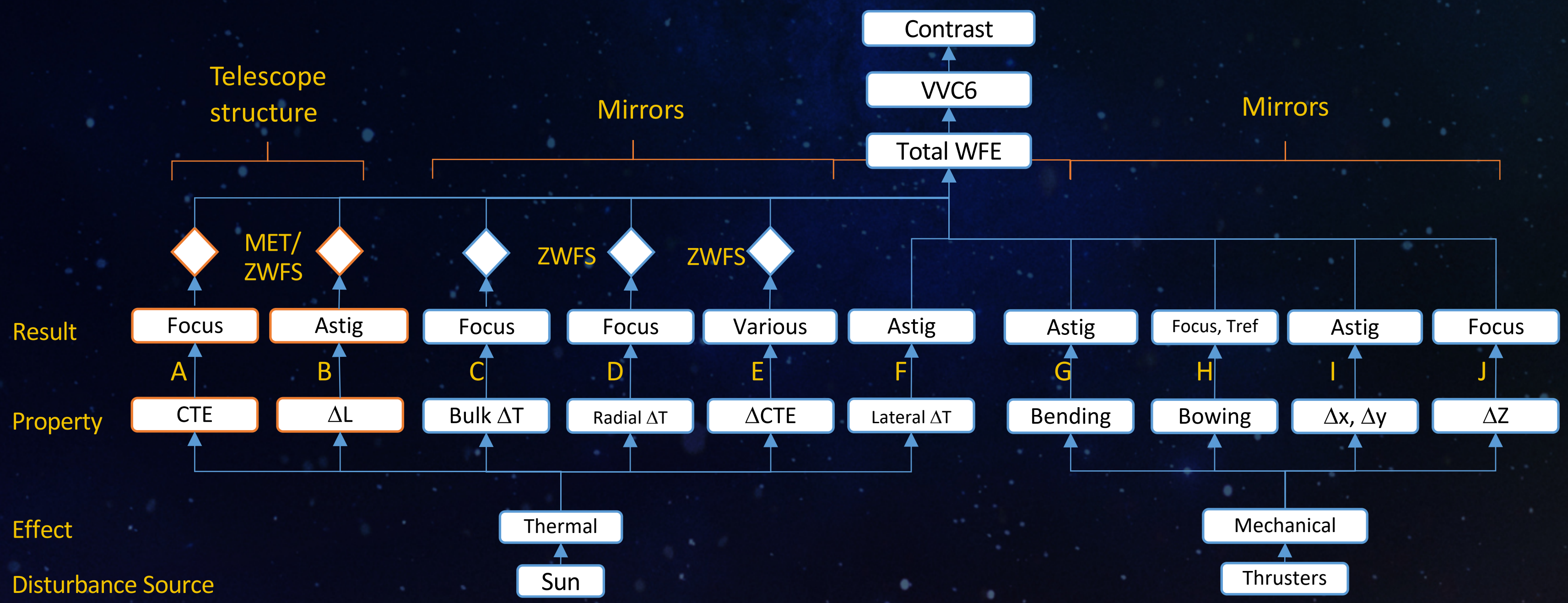
- Smooth and stable wavefront
- Stable mirror positions, pointing and wavefront
- Stable pointing and wavefront
- Stable mirror positions and mirror shape
- Stable mirror shape and wavefront
- Excellent low order aberration rejection

Designing for a Coronagraph

Coronagraph requires: Excellent wavefront quality and wavefront stability

Place system in a thermally and gravitationally benign Earth-Sun L2 orbit

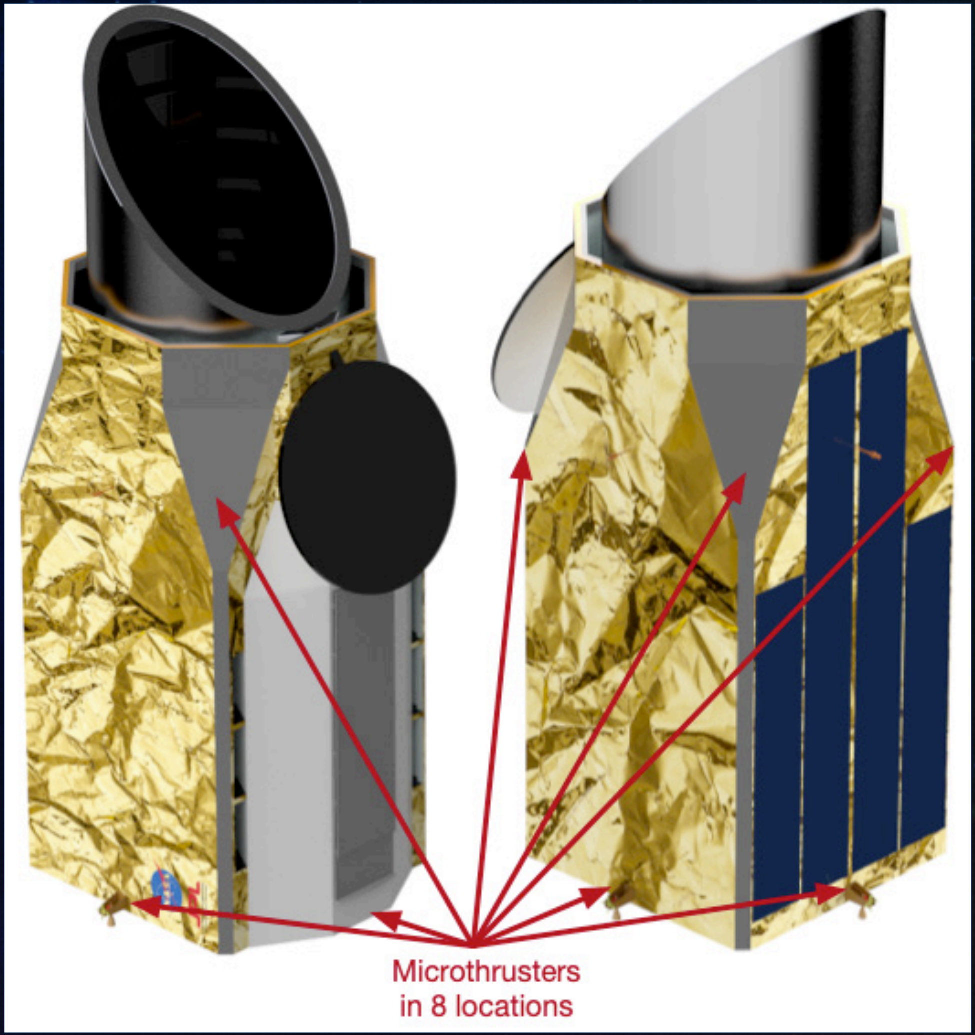
➡ And take account of at least these effects:



Telescope Spacecraft

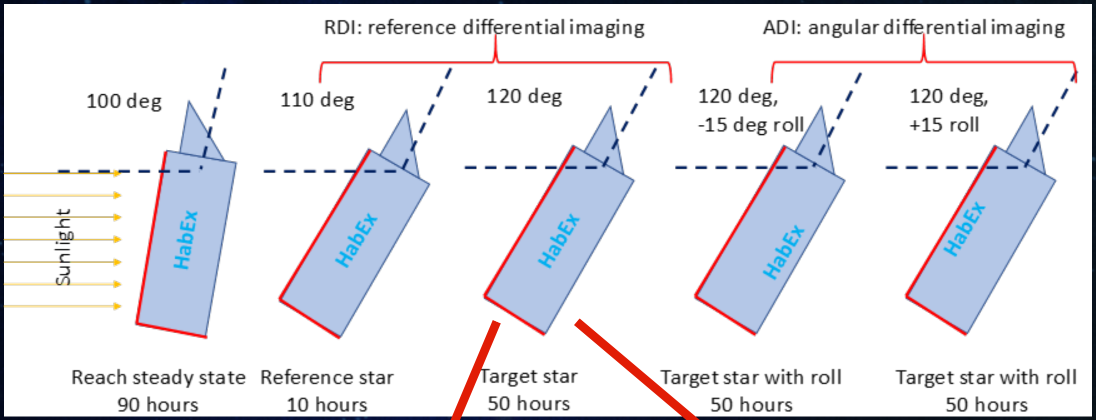
- Earth-Sun L2
  - Thermal stability
- Conventional thrusters for slewing
- Micro-Thrusters for fine pointing control
  - Dynamical disturbances orders of mag lower than reaction wheels
- Telescope barrel and secondary mirror tower isolated from the sunshade
- Monolithic primary mirror held stable at ~1 mK level within a thermal ‘bath’

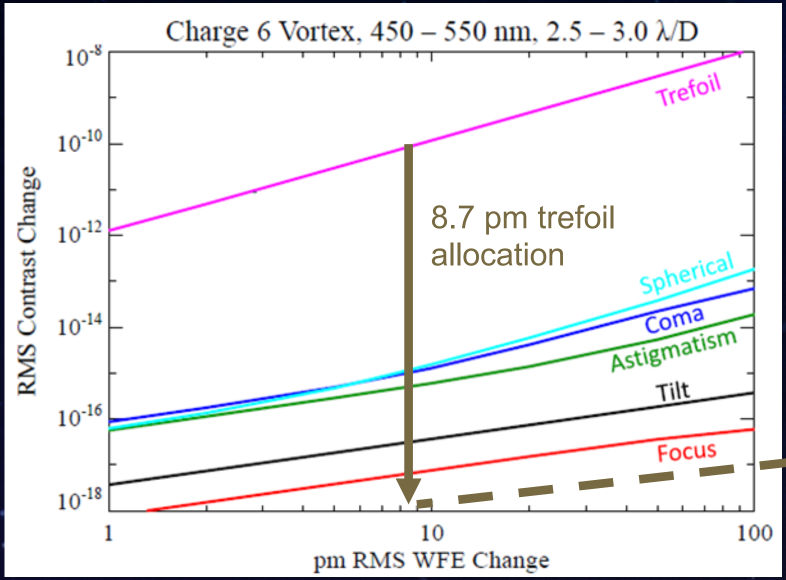
colloidal micro-thrusters on LISA Pathfinder

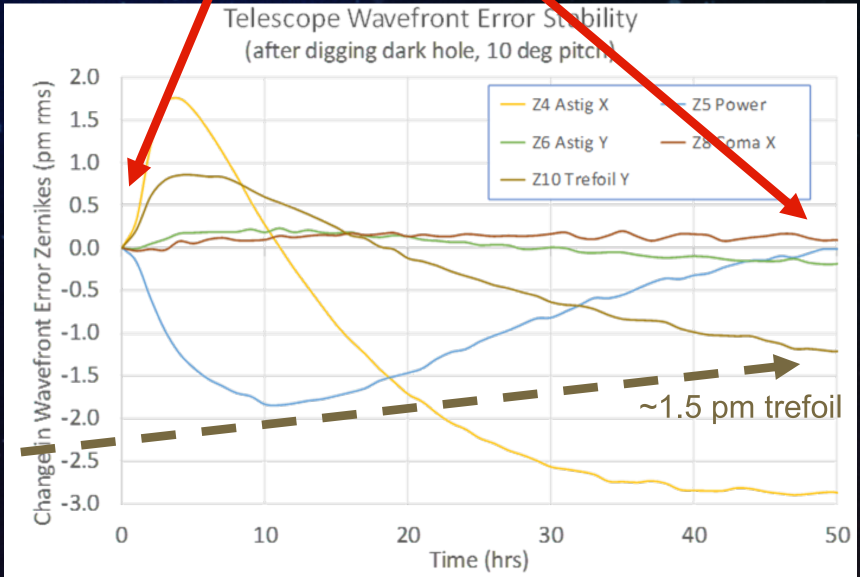


Operating the Coronagraph

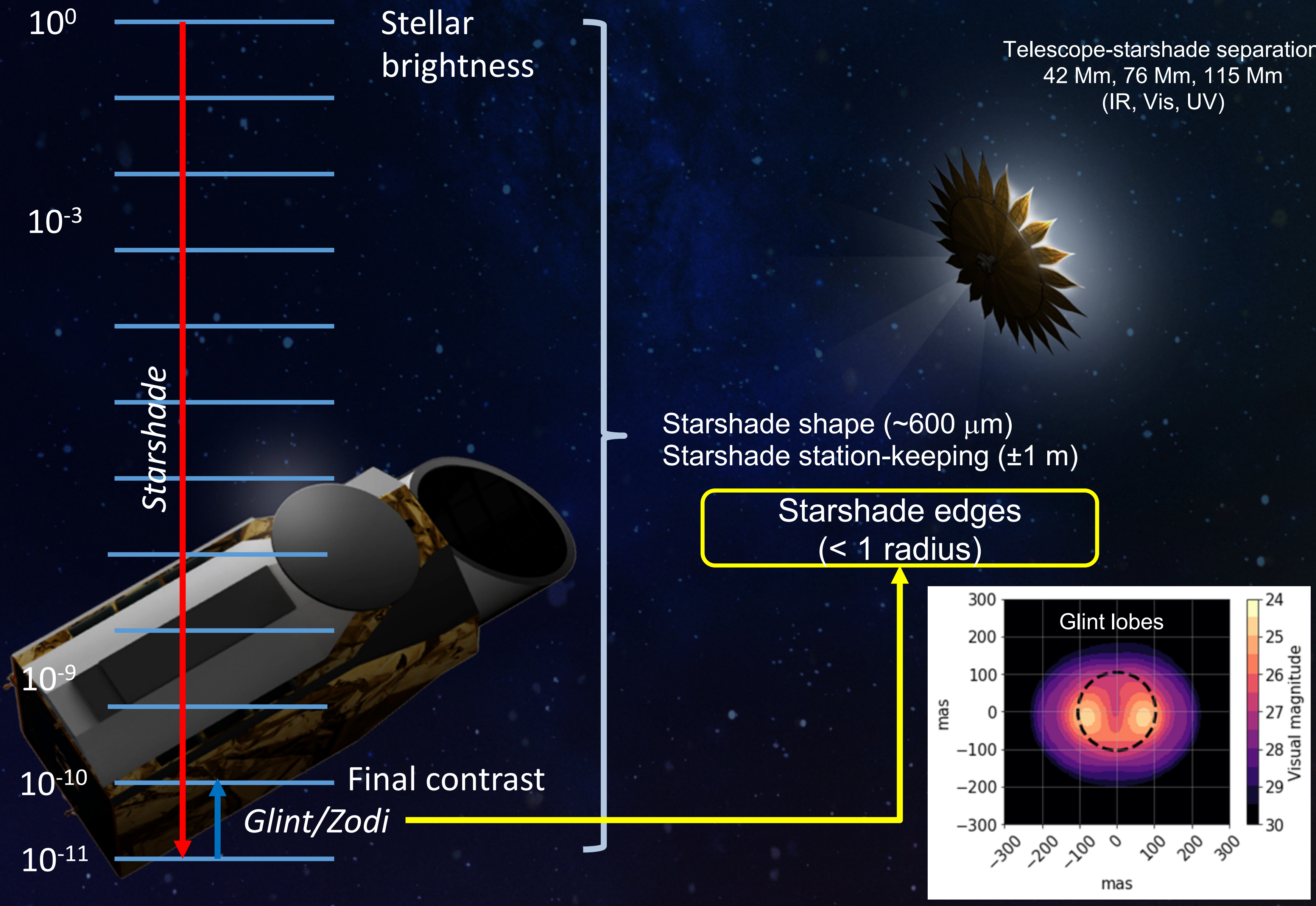
- RDI: telescope at L2 with a 100° sun angle
- Thermally equilibrate, then
  - Pitch to a reference star at an angle of 110°, hold for 10 hrs.
  - Dig dark hole on a reference star.
  - Pitch +10° to target star and hold for 50 hrs.



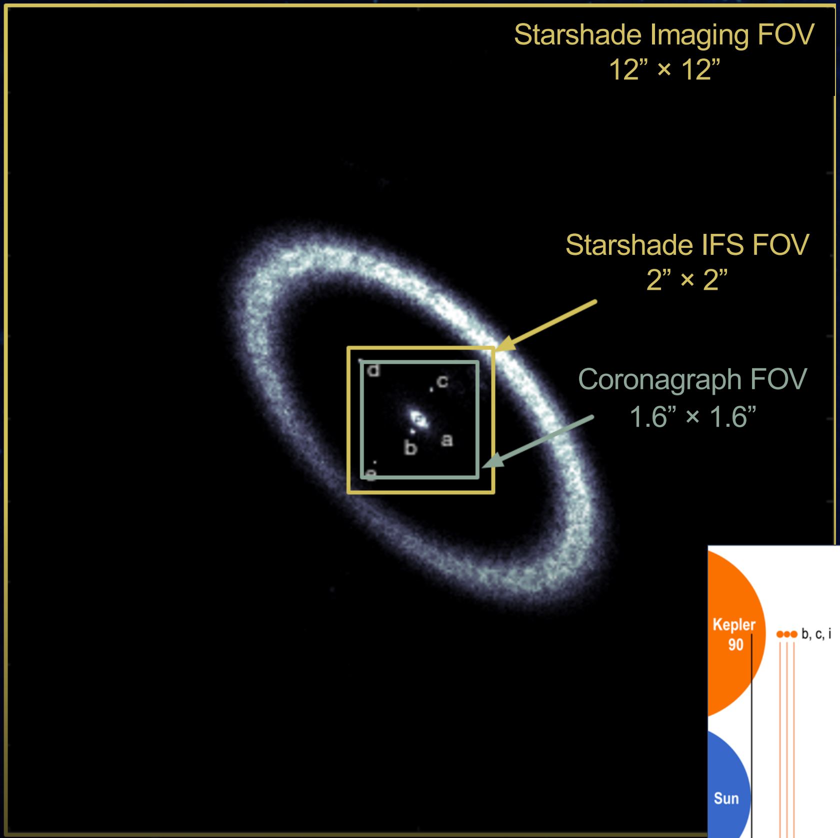




Starlight Suppression using a Starshade



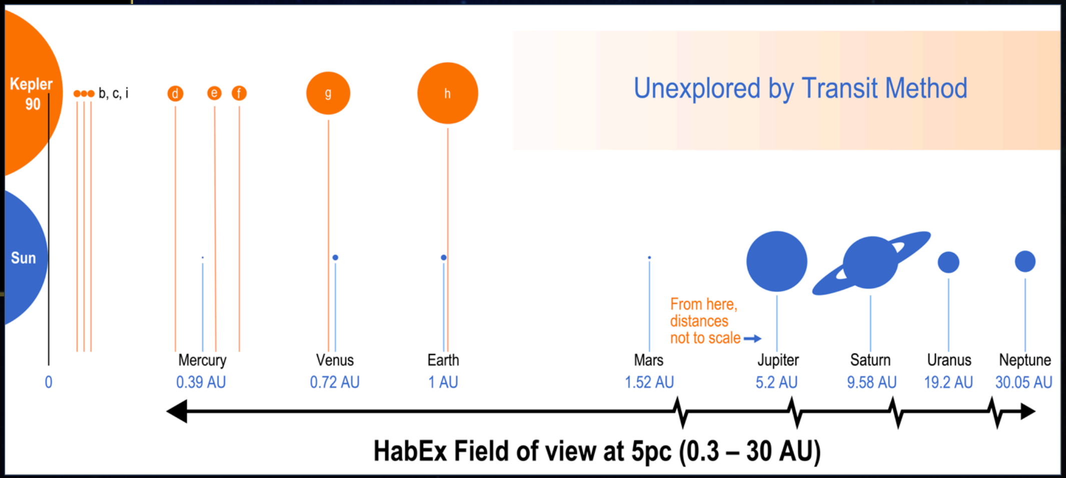
Exoplanet instruments: FOV



Starshade has high contrast and a large field of view, with OWA only limited by the detector format.

Starshade can cover a large range of physical separations in the nearest (most favorable) systems.

- Study planetary architecture diversity
- Assess “architecture habitability”
- Study variation of atmospheric properties



The Great Observatory for the 2030s & Beyond

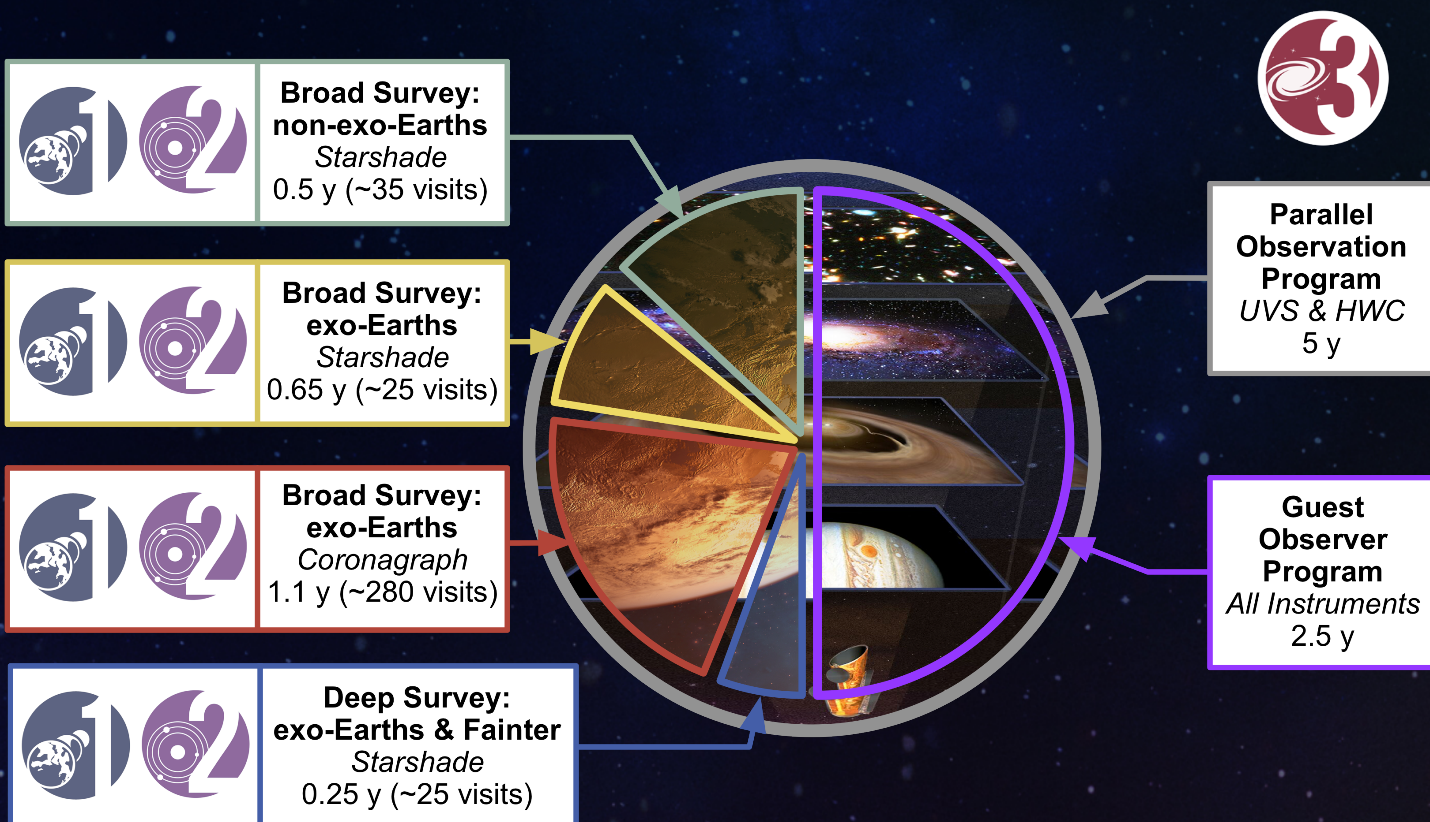
- HabEx will be a true successor to Hubble with:
  - A much larger effective collecting area in the UV,
  - State of the art instrumentation and detectors,
  - Better resolution than existing or planned facilities including HST, JWST, and WFIRST for wavelengths <1 micron.
- Directly detecting and characterizing Earth-like exoplanets orbiting sunlike stars in reflected visible light requires an ultra-stable space telescope.
- HabEx will be a technically superior observatory in every way, with
  - Extreme thermal stability ~1 mK
  - Extreme pointing stability ~0.7 mas
  - Extreme wavefront stability ~ 2 pm rms (over 50 hours)
  - Extreme maneuverability ~ 40°/minute slew rate

Backup slides

HabEx

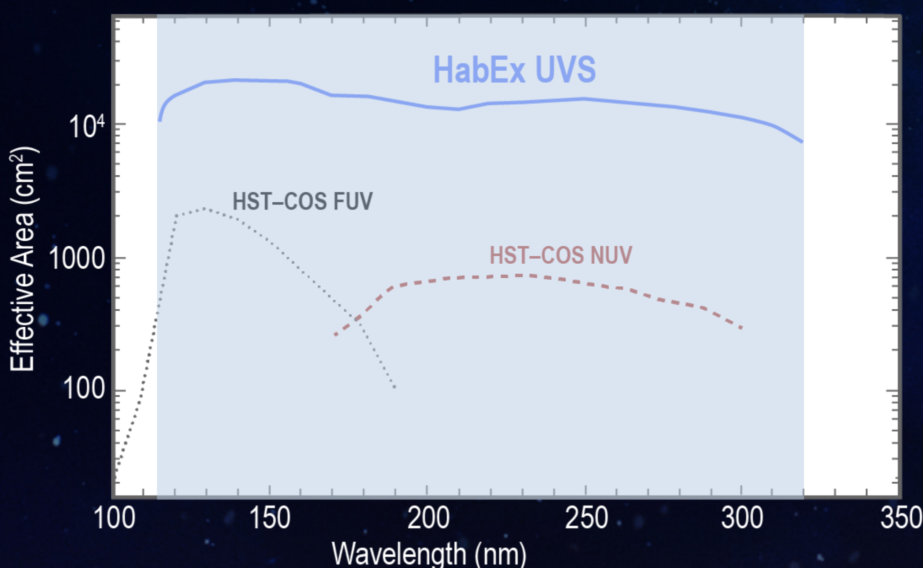
Notional Time Allocation for a 5-Year Mission

- Time is evenly split between exoplanet and observatory science
- Exoplanet broad-survey uses both the coronagraph (for multi-epoch imaging) and the starshade (for spectroscopy)
- The deep survey only uses the starshade for imaging and spectroscopy

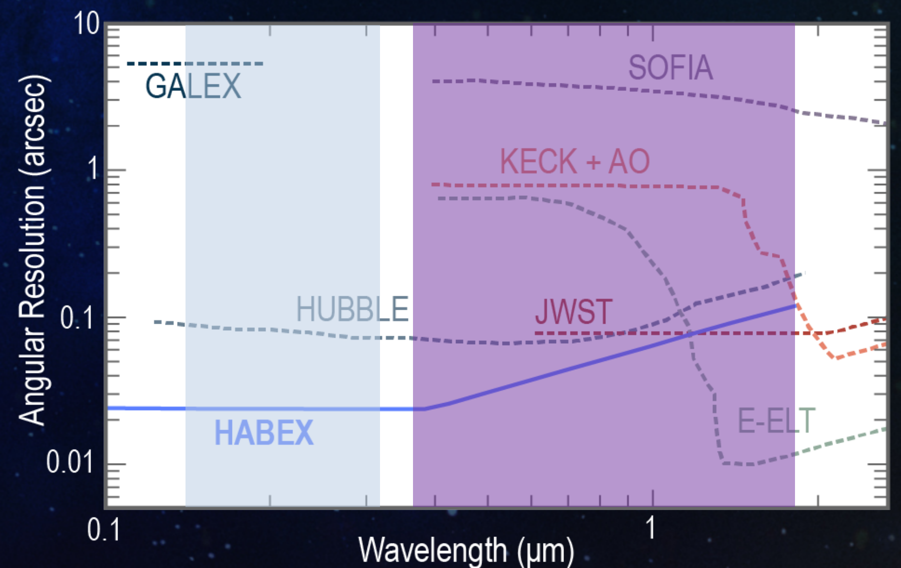


Exceptional Resolution and Effective Area

HabEx Ultraviolet Spectrograph (UVS)



HabEx Workhorse Camera (HWC)

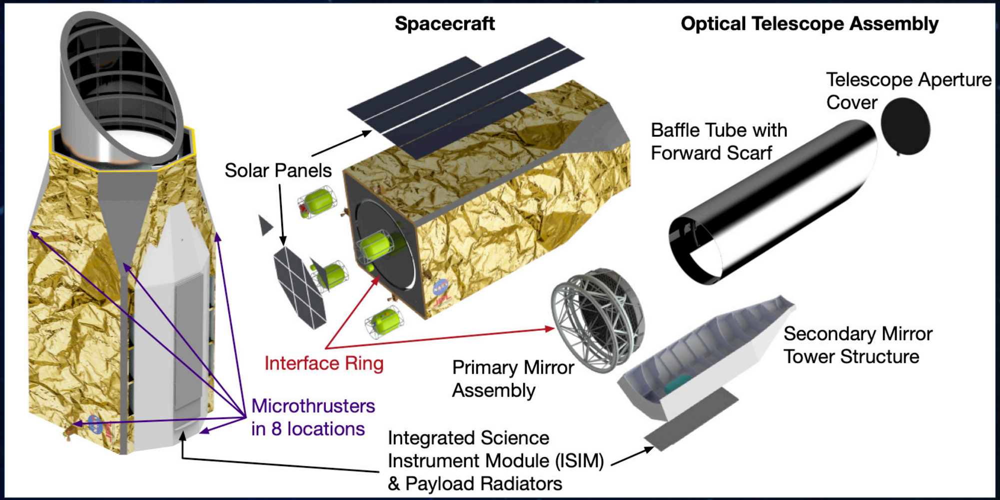


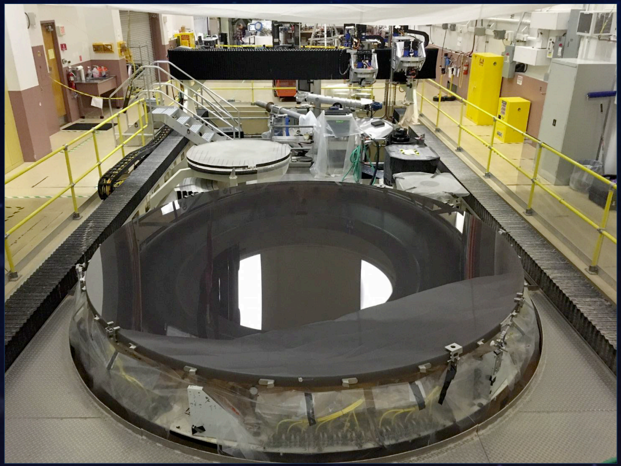
Telescope Accommodations

- High Mechanical Stability
  - Low Level of Disturbances (μ-thrusters)
  - Stiff Opto-Mechanical Structure
  - Ultra-low pointing jitter (<0.7 mas rms pre-correction)
  - Monolithic primary
    - No segment dynamic phasing issues

- High Thermal Stability
  - Active Thermal control
  - Zerodur PM / SM (< 5 ppb/K CTE)
  - Large Thermal Inertia (1400 kg PM)
  - Laser Metrology to rigidify M1-M2-M3

Section 6.2





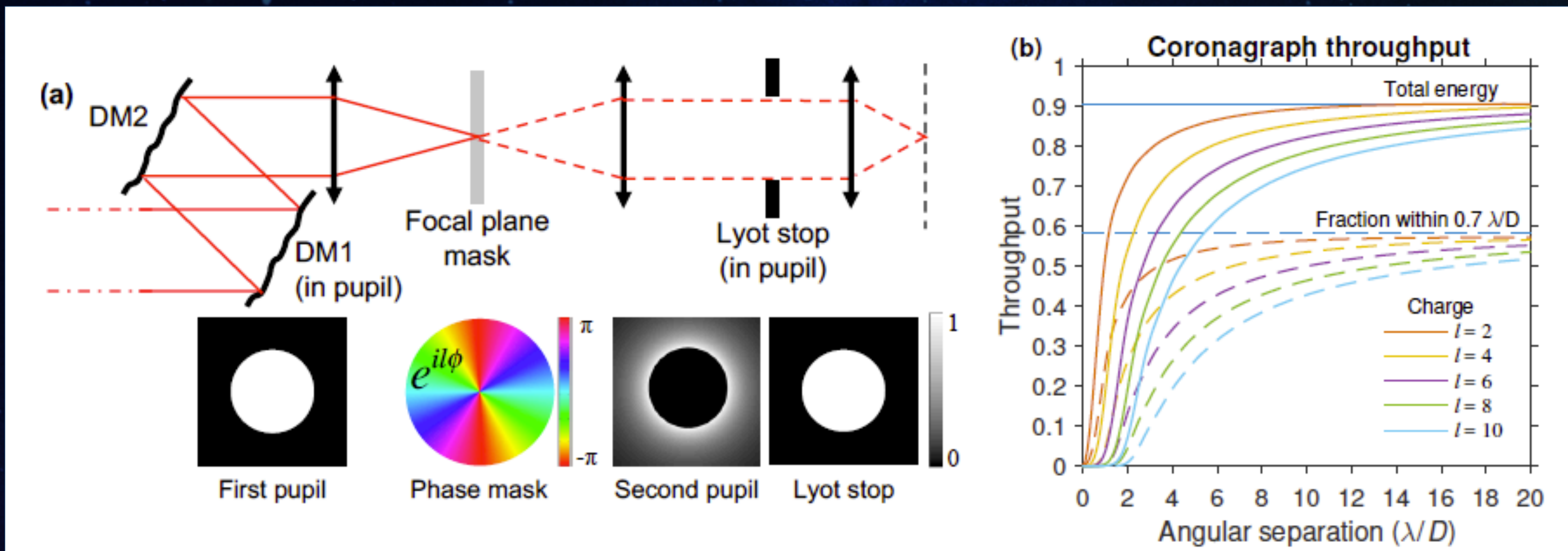
Daniel Inouye Telescope 4.2m Off Axis Primary Mirror (cast from Zerodur by Schott)

Coronagraph Accommodations and Trades

HabEx

Vector Vortex Charge 6 (VVC6) Coronagraph selected as best balance between:

- Science performance (IWA, throughput, overall planet yield)
- Resilience to low order aberrations (polarization cross-talk, thermal drift)



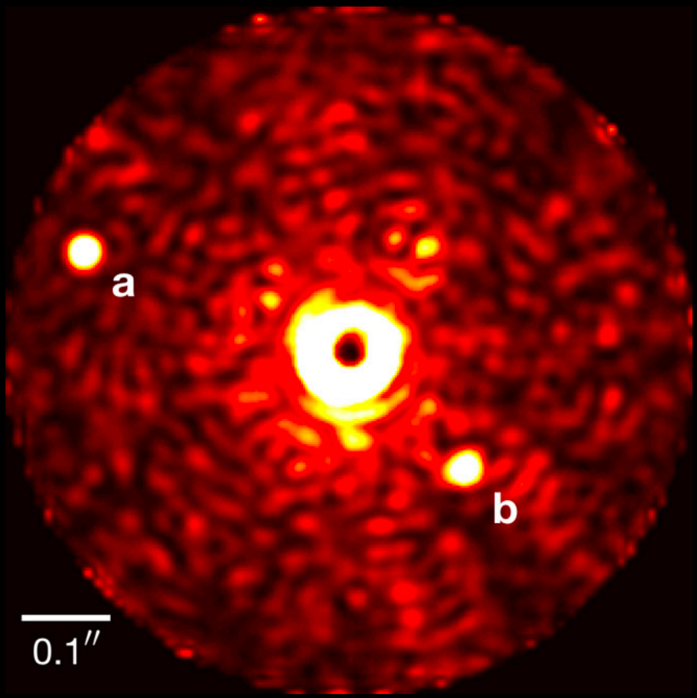
VVC6 → Telescope wavefront stability requirements can be relaxed and met

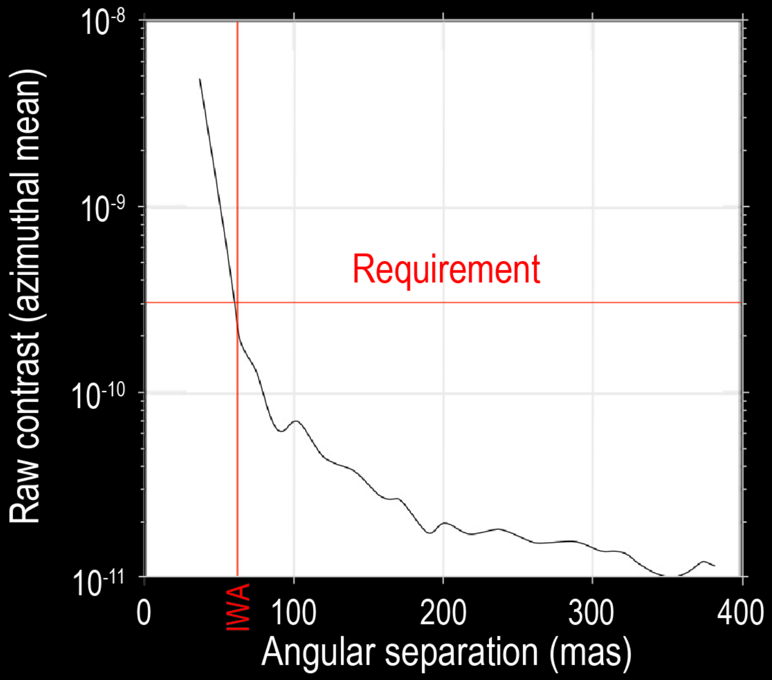
Dimitri Mawet's presentation on the State-of-the-art of Coronagraphy

HabEx

Verifying the Telescope - Coronagraph System: Static Modeling (J. Krist 2019)

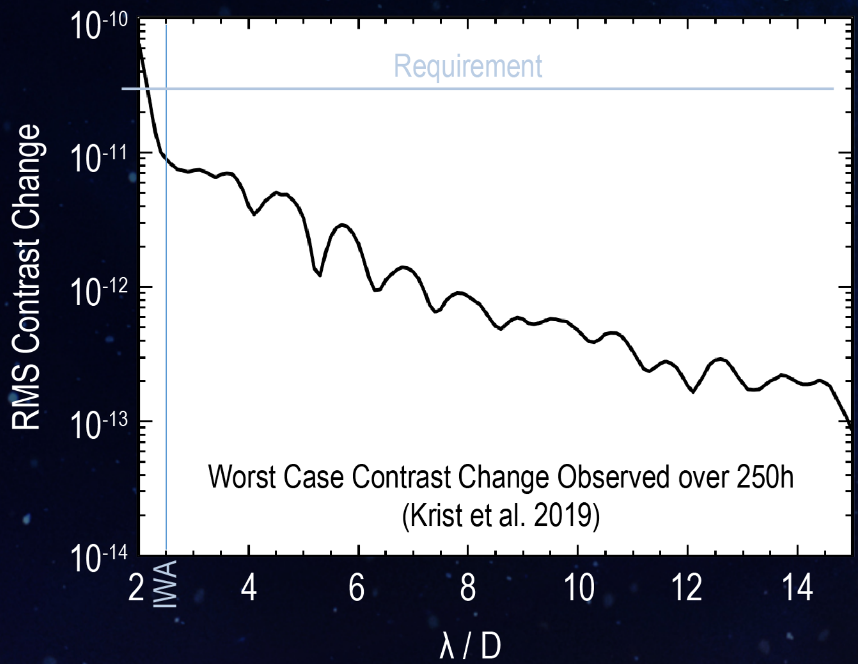
End-to-end dual polarization numerical modeling developed for previous mission concept studies & technology demonstrations, lab-validated on WFIRST-CGI





Verifying the Telescope - Coronagraph System: Dynamic Modeling Results

Predicted Wavefront Error Stability meets contrast stability requirements

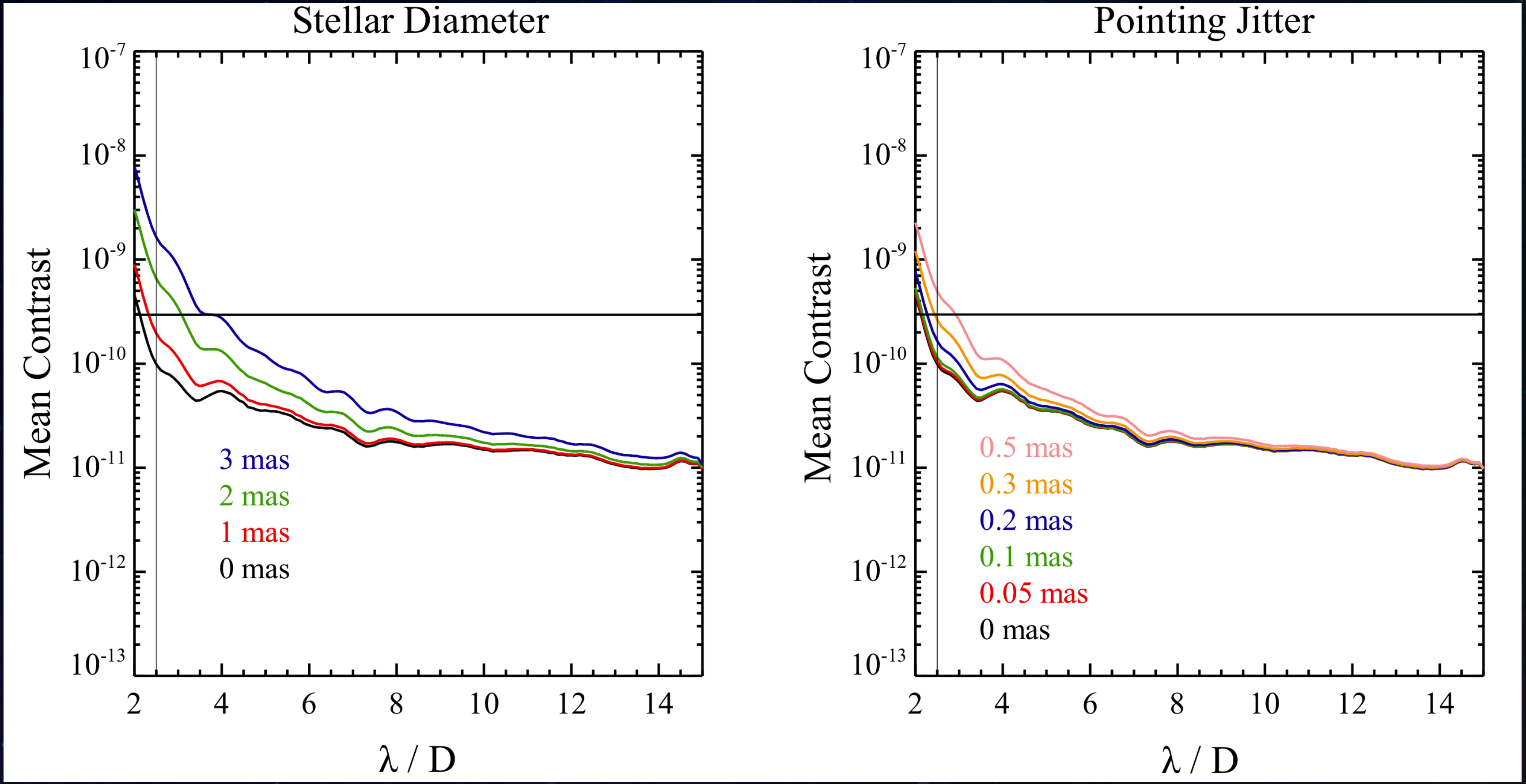


Section 6.9, Figure 6.9-24

Coronagraph Modeling includes:

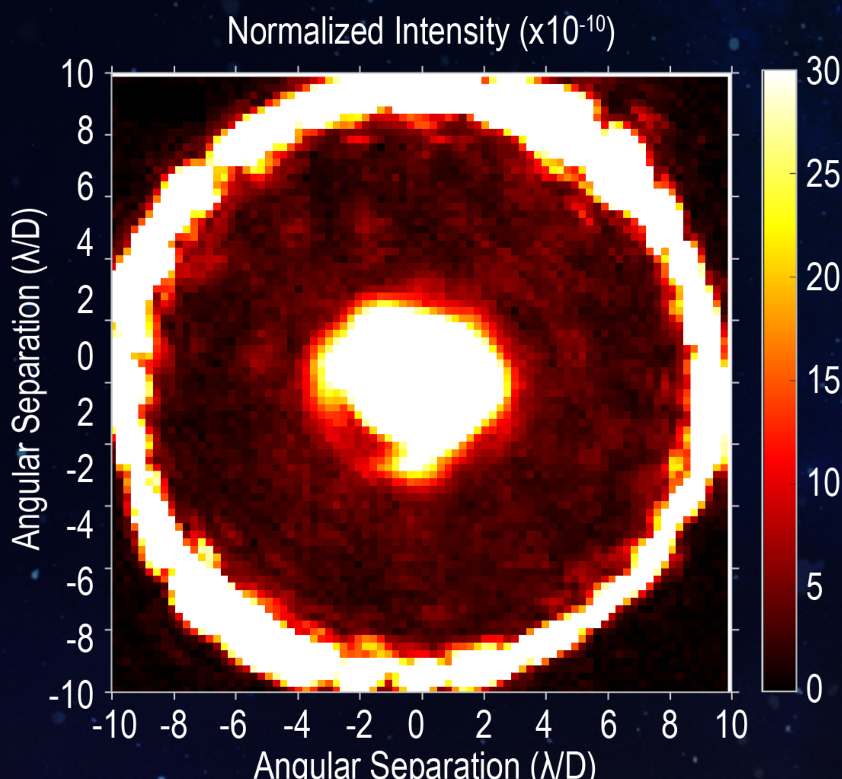
- Realistic static wavefront errors WFE (A, ϕ)
- WFE drifts predicted from STOP analysis
- Finite diffraction propagation effects
- Polarization-induced aberrations
- Finite star diameter and pointing errors
- VVC 6 sensitivity to WFE

HabEx Coronagraph Modeling Results



Coronagraph and Starshade Laboratory Already Approach Requirements

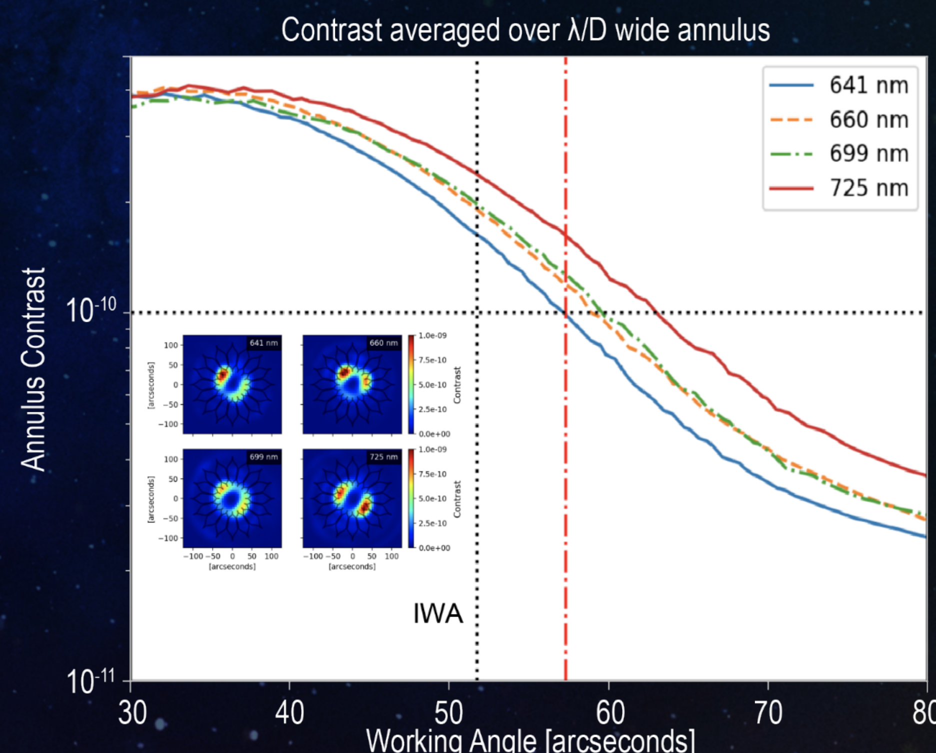
10% bandwidth dark holes reach 4×10^{-10} mean contrast with *HabEx-like unobscured monolithic aperture* and classical Lyot Coronagraph



Decadal Survey Testbed (DST) Results: Seo, B. et al. 2019

Dimitri Mawet's presentation on the State-of-the-art of Coronagraphy

Starshade testbed reaches better than $3x10^{-10}$ broad-band contrast at IWA, at a flight-like Fresnel #



Anthony Harness et al. 2019, Princeton Lab Starshade Testbed Results https://exoplanets.nasa.gov/exep/technology/starshade/)

Kendra Short's presentation on Technology Readiness for Starshades

Architectures vs Science, Cost and Technical Maturity

HabEx

HabEx Science Goals & Objectives		HabEx Mission Architectures								
		4H	4C	4S	3.2H	3.2C	3.2S	2.4H	2.4C	2.4S
Habitable Exoplanets	O1 Exo-Earth candidates around nearby sunlike stars?									
	O2 Water vapor in rocky exoplanet atmospheres?									
	O3 Biosignatures in rocky exoplanet atmosphere?									
	O4 Surface liquid water on rocky exoplanets?									
Exoplanetary Systems	O5 Architectures of nearby planetary systems?									
	O6 Exoplanet atmospheric variations in nearby systems?									
	O7 Water transport mechanisms in nearby planetary systems?									
	O8 Debris disk architectures in nearby planetary systems?									
Observatory Science	O9 LIfecycle of baryons?									
	O10 Sources of reionization?									
	O11 Origins of the elements?									
	O12 Discrepancies in measurements of the cosmic expansion rate?									
	O13 The nature of dark matter?									
	O14 Formation and evolution of globular clusters?									
	O15 Habitable conditions on rocky planets around M-dwarfs?									
	O16 Mechanisms responsible for transition disk architectures?									
	O17 Physics driving star-planet interactions, *e.g.* auroral activity?									
Estimated Cost ($B FY20)		6.8	4.8	5.7	5.7	3.7	5.0	4.8	3.1	4.0
Number of TRL4		13	10	9	12	9	9	11	8	8
Exo-Earths Characterized		8	5	5	5	3	4	3	1	2
Exoplanet Detections (all)		178	114	140	105	83	119	76	27	67

- *STDT's preferred architecture is 4H*
- *Red does not mean "no science"*
- *At a given size, Hybrid architectures maximize exoplanet science*
- *C-only*
  - *no UV exoplanet observations*
  - *Vast majority of planets with orbits*
  - *Reduced spectroscopy*
- *S-only:*
  - *High Quality spectra*
  - *Limited # of orbits measured*

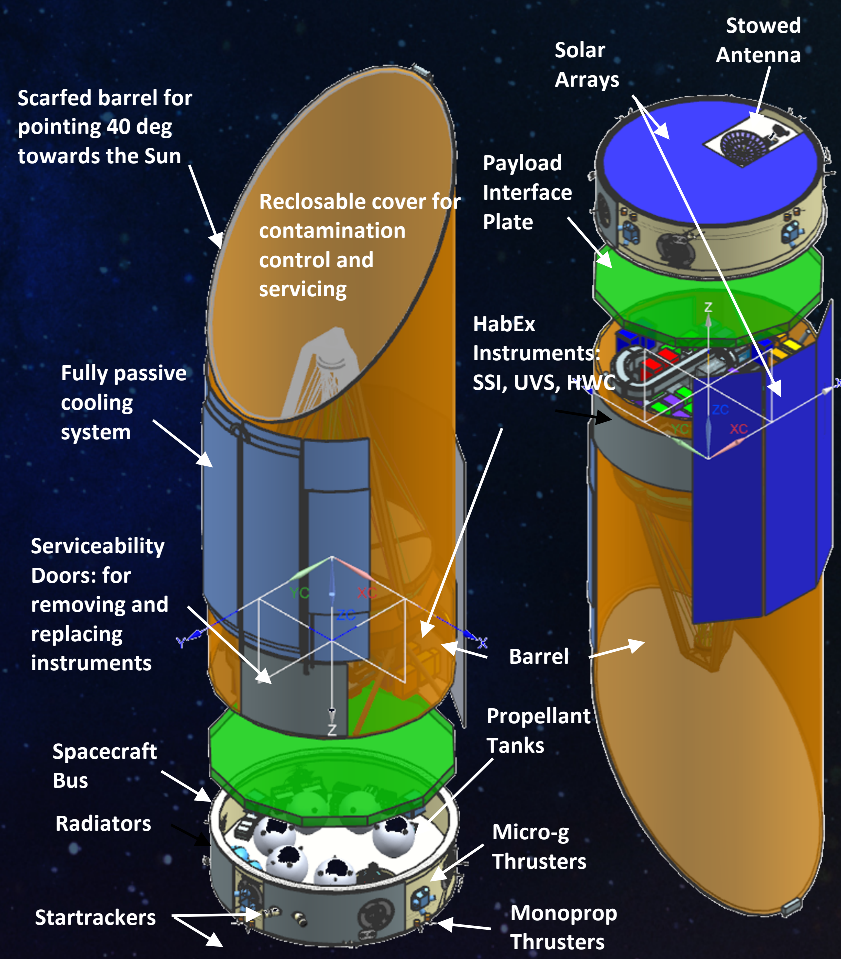
- *Observatory Science is primarily a function of telescope size*

- *Architectures 4H (4C) and 3.2S studied in detail and "TRACEable"*

HabEx Starshade-Only 3.2S Architecture

- No coronagraph
  - –Telescope WFE stability tolerances relaxed 1000 times
  - –Starshade provides the highest quality exoplanet spectroscopy
  - –*But* – lower yield of exo-Earths *unless detected before HabEx*
- Active Optics On-axis Telescope
  - –Corrects Static PM WFE in orbit
  - –Segmented to stay within current practice and largest ULE mirrors
  - –Laser MET to continuously maintain optical alignment
  - –Lighter (2T) & Smaller Telescope
    - Light weight ULE (5cm thick) Primary Mirror
    - *Total* launch Mass = 7.3 T, fits in Delta IV Heavy or Vulcan Centaur
    - More compact (f/1.3)
    - Non deployable OTA a priori scalable to 4m and above
- Lower cost option

Estimated Cost Reductions	**HabEx 4H**	**HabEx 3.2S**
Smaller Telescope	–	-0.6 $B
No Coronagraph	–	-0.4 $B
Smaller Launch Vehicle	–	-0.4 $B
Same Starshade System	–	–
Lower Reserves	–	-0.4 $B
Total Estimated Cost	**6.8 $B**	**5.0 $B**

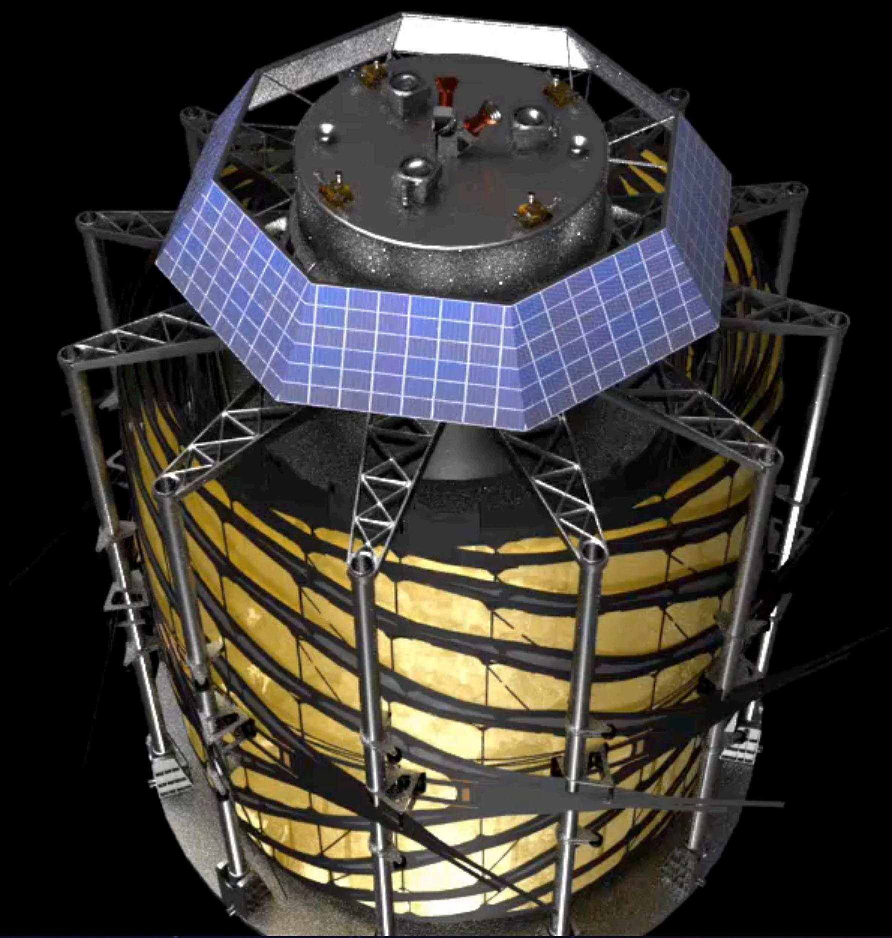


Appendix B

Take-Aways on HabEx Architecture

1. Conservative
2. Achievable
3. Balanced
4. Flexible

Starshade Deployment



Truss Deployment Test

½ scale truss for HabEx

½ scale for HabEx

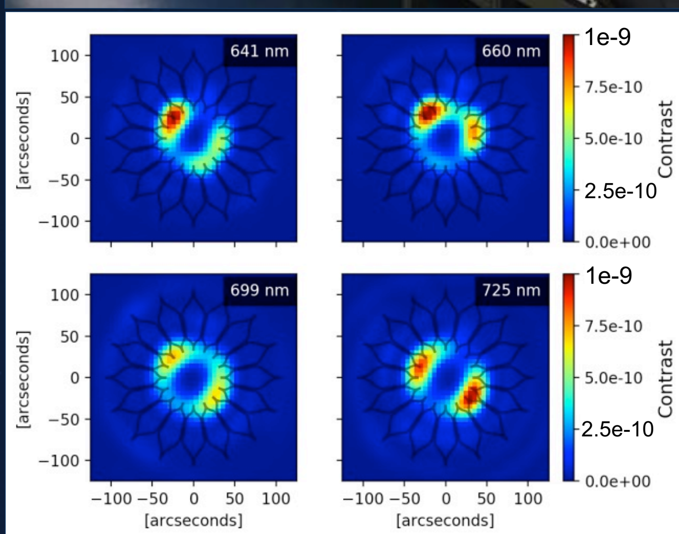
HabEx

Starshade Technology Advances

NASA

TRL 5 March 2020

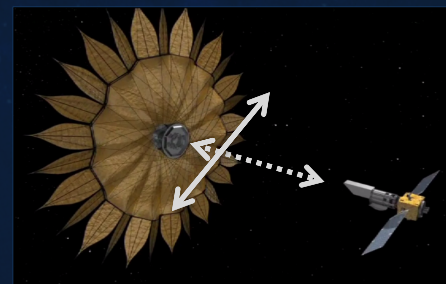
Starlight Suppression

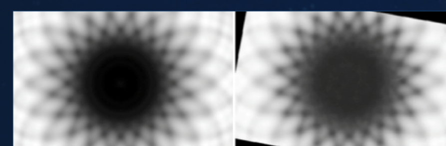


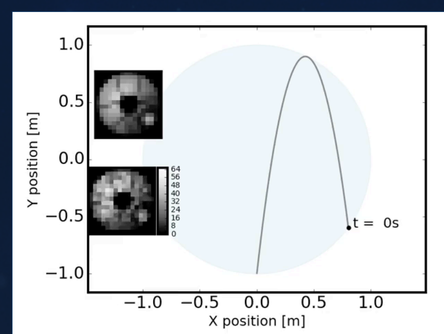
1 × 10^{-10} Contrast over 10% bandwidth

TRL 5

Lateral Formation Sensing



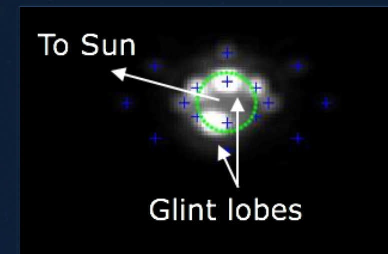


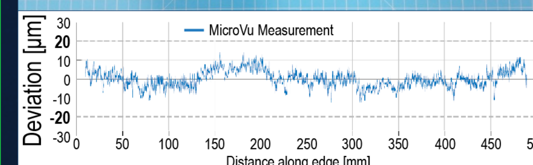


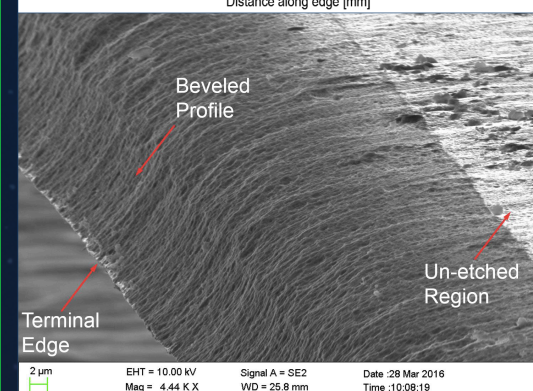
<1 m lateral displacement

TRL 5

Controlling Scattered Sunlight





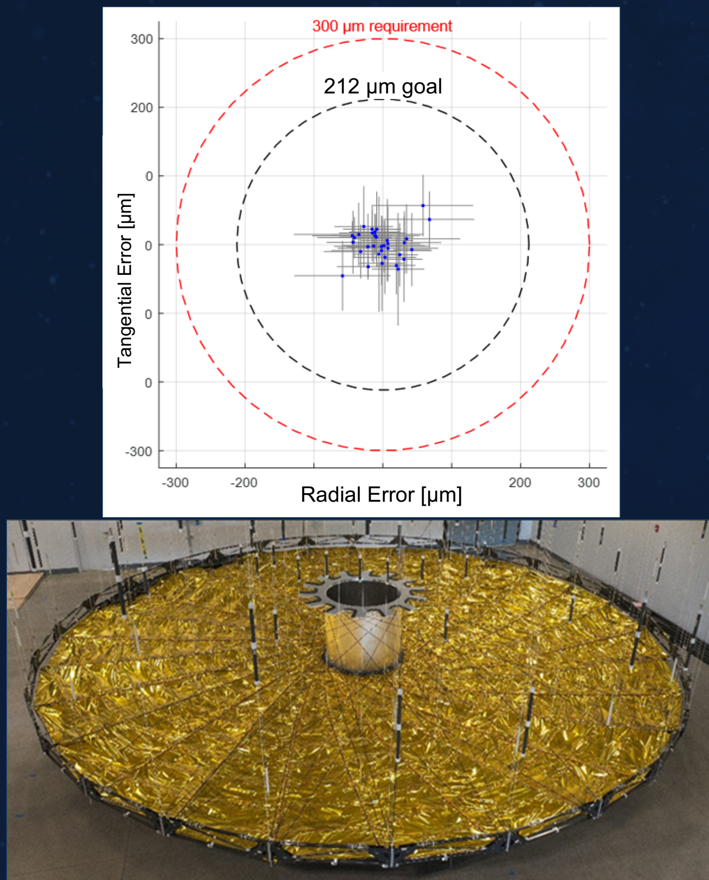


<20 μm out of plane edge

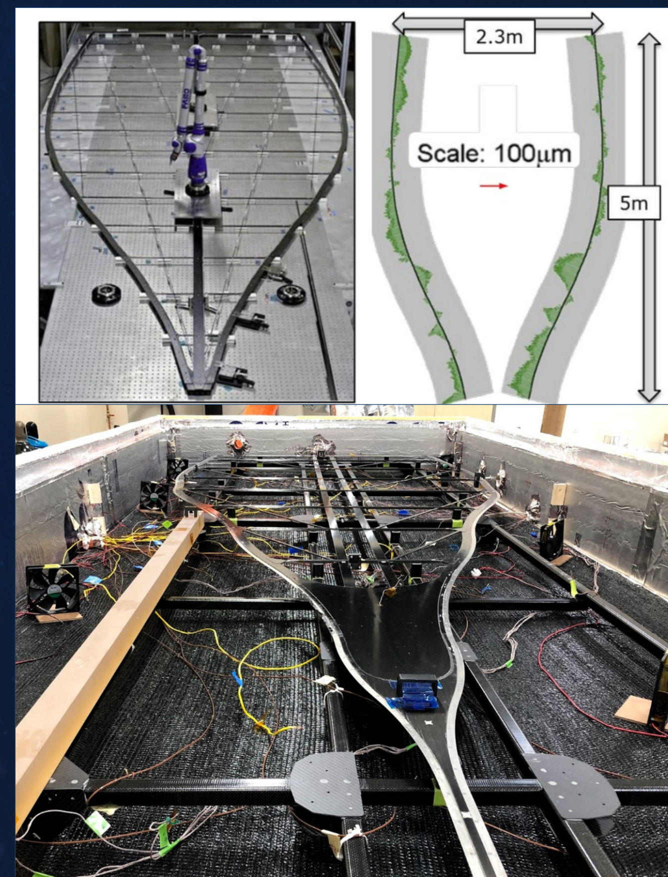
Starshade Technology Advances

TRL 4

Petal Deployment Accuracy and Shape Stability



<300 µm petal deployment accuracy



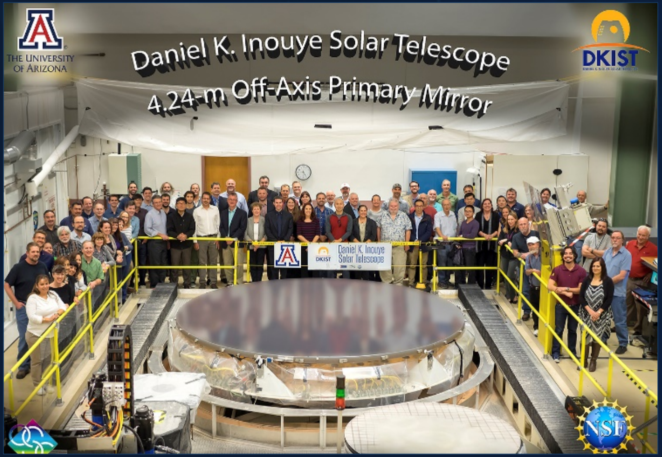
<140 µm petal shape accuracy

HabEx

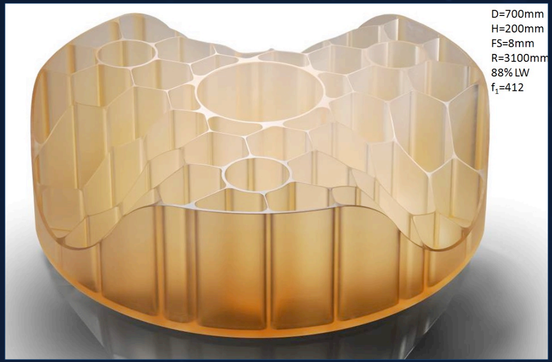
Telescope Technology Advances

TRL 4

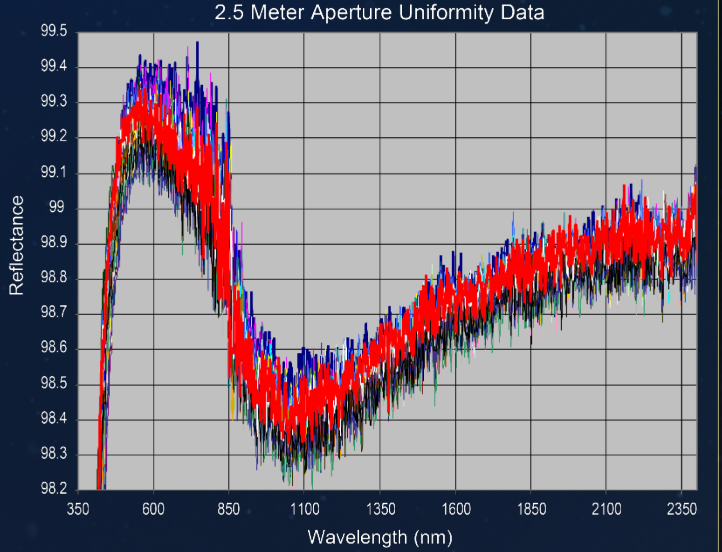
Large Monolith Mirror Fabrication



Surface figure error (rms): <19 nm; 5 nm (1–100 mm period), 0.1 nm surface roughness CTE ±3 ppb/K

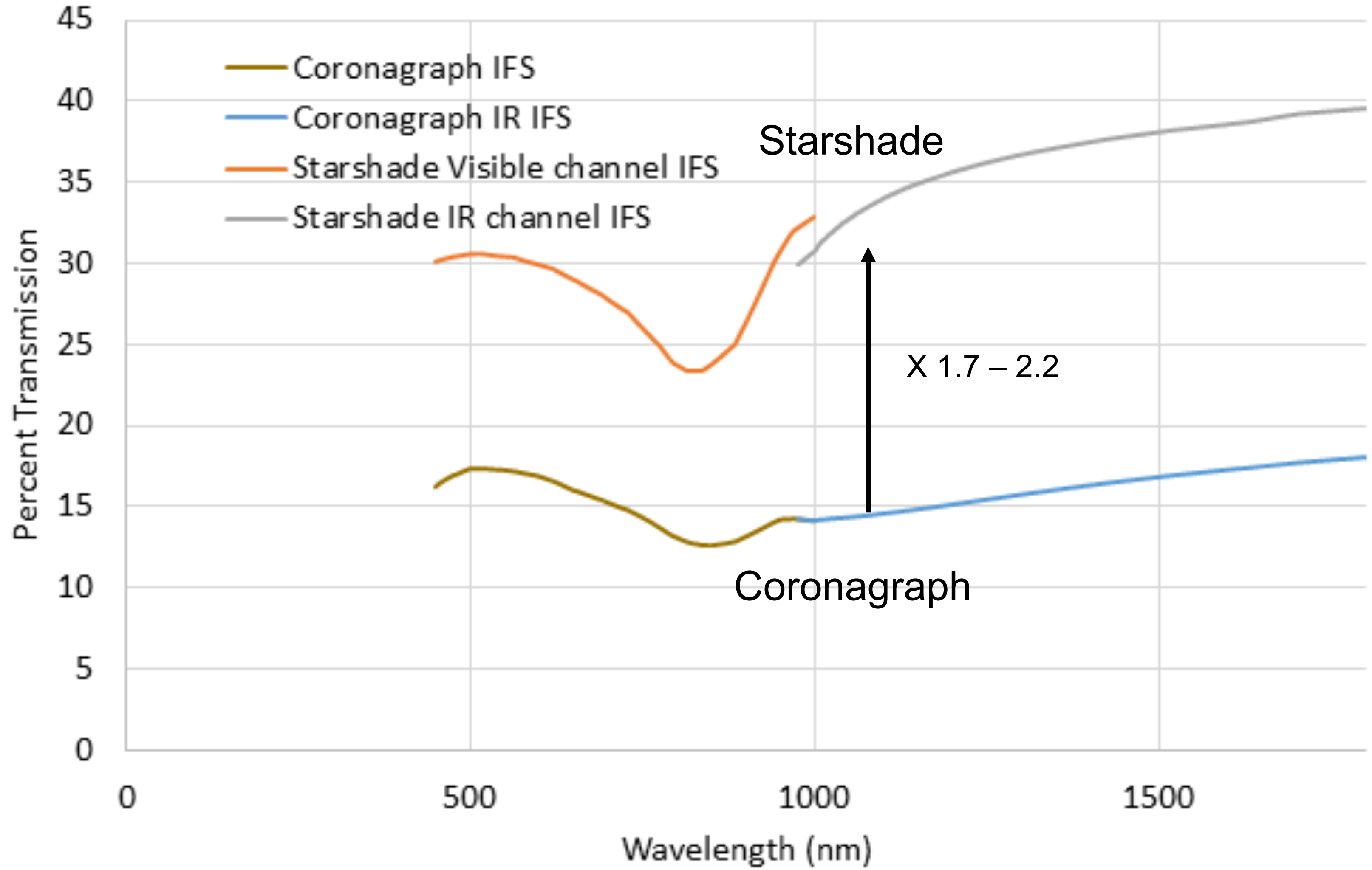


2 mm thick machined ribs



~0.5% Reflectance variation
2.5 m "diameter", 34 samples protected silver

Transmission Curves Coronagraph and Starshade IFS



Transmission Curves
Coronagraph and Starshade Cameras